

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION  
International Bureau

BN

## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> : F02B 43/10, F02M 25/12	A1	(11) International Publication Number: WO 95/06194						
		(43) International Publication Date: 2 March 1995 (02.03.95)						
<p>(21) International Application Number: PCT/US94/09414</p> <p>(22) International Filing Date: 18 August 1994 (18.08.94)</p> <p>(30) Priority Data:</p> <table border="0"><tr><td>08/110,057</td><td>20 August 1993 (20.08.93)</td><td>US</td></tr><tr><td>08/196,701</td><td>15 February 1994 (15.02.94)</td><td>US</td></tr></table> <p>(71) Applicant: MASSACHUSETTS INSTITUTE OF TECHNOLOGY [US/US]; 77 Massachusetts Avenue, Cambridge, MA 02139 (US).</p> <p>(72) Inventors: RABINOVICH, Alexander; Apartment C50, 1000 Loring Avenue, Salem, MA 01970 (US). COHN, Daniel, R.; 26 Walnut Hill Road, Chestnut Hill, MA 02168 (US). BROMBERG, Leslie; 176 Wilshire Drive, Sharon, MA 02067 (US).</p> <p>(74) Agent: PASTERNAK, Sam; Choate, Hall &amp; Stewart, Exchange Place, 53 State Street, Boston, MA 02109 (US).</p>		08/110,057	20 August 1993 (20.08.93)	US	08/196,701	15 February 1994 (15.02.94)	US	<p>(81) Designated States: AM, AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, ES, FI, GB, GE, HU, JP, KE, KG, KP, KR, KZ, LK, LT, LU, LV, MD, MG, MN, MW, NL, NO, NZ, PL, PT, RO, RU, SD, SE, SI, SK, TJ, TT, UA, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG), ARIPO patent (KE, MW, SD).</p> <p>Published</p> <p><i>With international search report.</i></p> <p><i>Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i></p>
08/110,057	20 August 1993 (20.08.93)	US						
08/196,701	15 February 1994 (15.02.94)	US						
(54) Title: PLASMATRON-INTERNAL COMBUSTION ENGINE SYSTEM								
<p>(57) Abstract</p> <p>Rotary power system. The system includes a source of hydrocarbon fuel which is supplied to a plasmatron which reforms the fuel into hydrogen-rich gas. An internal combustion engine is connected to receive the hydrogen-rich gas from the plasmatron. The engine powers an electrical generator and the generated electricity is connected to the plasmatron. In one embodiment, the engine also receives hydrocarbon fuel along with the hydrogen-rich gas. The combination of plasmatron and internal combustion engine results in lowered exhaust emissions. The plasmatron may include water plasmatrons and partial oxidation plasmatrons.</p>								

**FOR THE PURPOSES OF INFORMATION ONLY**

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	GB	United Kingdom	MR	Mauritania
AU	Australia	GE	Georgia	MW	Malawi
BB	Barbados	GN	Guinea	NE	Niger
BE	Belgium	GR	Greece	NL	Netherlands
BF	Burkina Faso	HU	Hungary	NO	Norway
BG	Bulgaria	IE	Ireland	NZ	New Zealand
BJ	Benin	IT	Italy	PL	Poland
BR	Brazil	JP	Japan	PT	Portugal
BY	Belarus	KE	Kenya	RO	Romania
CA	Canada	KG	Kyrgyzstan	RU	Russian Federation
CF	Central African Republic	KP	Democratic People's Republic of Korea	SD	Sudan
CG	Congo	KR	Republic of Korea	SE	Sweden
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LU	Luxembourg	TD	Chad
CS	Czechoslovakia	LV	Latvia	TG	Togo
CZ	Czech Republic	MC	Monaco	TJ	Tajikistan
DE	Germany	MD	Republic of Moldova	TT	Trinidad and Tobago
DK	Denmark	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	US	United States of America
FI	Finland	MN	Mongolia	UZ	Uzbekistan
FR	France			VN	Viet Nam
GA	Gabon				

## PLASMATRON-INTERNAL COMBUSTION ENGINE SYSTEM

This is a continuation-in-part of co-pending application U.S.S.N.

08/110,057 filed August 20, 1993.

5

### BACKGROUND OF THE INVENTION

This invention relates to rotary power systems including a plasmatron for supplying hydrogen-rich gas to an internal combustion engine.

Hydrogen is attractive as a fuel or additive for internal combustion engines because hydrogen as a fuel source can significantly reduce air pollution and can also serve as an alternative energy source to gasoline. See Mishchenko, A. I. et al., Proc. VII World Hydrogen Energy Conference, Vol. 3 (1988), Belogub, A. V. and G. B. Talda, Int. J. Hydrogen Energy, Vol. 16, 423 (1991), Varde, K.S. and L.K. Varde Hydrogen Energy Progress V, Vol. 4 (1984), Feucht, K., W. Hurich, N. Komoschinski, and R. Povel, Int. J. Hydrogen Energy, Vol 13, 243 (1988), Chuveliov, A.V., In: *Hydrogen Energy and Power Generation*, T. Nejat Veziroglu, Ed., Nova Science Publisher, New York, New York (1991), Das, L.M., Int. J. Hydrogen Energy, Vol 16, 765 (1991). Moreover, engine efficiency can be 10-50% higher when running on hydrogen as compared with a gasoline engine. Prior art systems contemplated either storing hydrogen on-board or generating it on board. On-board storage requires high pressure vessels, cryogenic containers if the hydrogen is to be stored as a compressed gas or liquid, or large getter volumes and weights if the hydrogen is to be stored as a hydride. Moreover, the refill time for hydrogen is substantially longer than that for gasoline when the hydrogen is to be stored on-board.

As to the on-board production of hydrogen, several approaches have been disclosed in the prior art. For example, United States Patent No. 5,143,025 discloses the use of electrolysis to separate water into hydrogen and oxygen and introducing the hydrogen into an internal combustion engine. In United States Patent No. 5,159,900, hydrogen gas is produced by water interaction with solid carbon. Electrical current is passed between the carbon

electrodes causing the electrodes to burn and oxidize to form carbon monoxide and hydrogen. U.S. Patent No. 5,207,185 discloses a burner which utilizes a portion of the hydrocarbon fuel to reform another portion to produce hydrogen. The hydrogen is then mixed with the hydrocarbon fuel for  
5 introduction into an internal combustion engine.

Another system diverts a fraction of the gasoline from the flow path to the engine and is passed through a catalytic converter and decomposed to yield hydrogen-rich gas. See, Breshears, R., Cotrill, H. and Rupe, J., Proc. of EPA 1st Symposium on Low Pollution Power Systems Development, 268  
10 (1973). We note that the authors state that this catalytic converter system would not be practical to generate hydrogen as the sole fuel for an engine. This article also suggests other techniques for generating hydrogen on-board a vehicle. Yet another system of this type uses partial oxidation in a catalytic converter to produce hydrogen rich gas. See Houseman, J. and Voecks, G.E.,  
15 Proc. 3rd World Hydrogen Energy Conf., 949 (1980). This system requires carefully controlled catalytic action and temperature range and has limitations for startup and transient response.

### SUMMARY OF THE INVENTION

20 The rotary power system of the invention includes a source of hydrocarbon fuel and a plasmatron for receiving the hydrocarbon fuel and reforming it into a hydrogen-rich gas. An internal combustion engine receives the hydrogen-rich gas from the plasmatron and a generator powered by the engine delivers electrical energy to operate the plasmatron. Optionally, the  
25 engine is connected to receive hydrocarbon fuel directly in addition to the hydrogen rich gas. Thus, the system can be readily switched from 100% hydrocarbon fuel to a mode in which hydrogen-rich gas serves as an additive to the hydrocarbon fuel and then to operation with 100% hydrogen-rich gas. In preferred embodiments, the plasmatron is a water plasmatron utilizing

steam reforming of the hydrocarbon source fuel. In another embodiment, the plasmatron is used in a partial oxidation reforming mode.

Because the plasmatron is highly efficient and also because there is the option to operate in a mode where only part of the hydrocarbon fuel is converted into hydrogen-rich gas, the overall system efficiency remains high even though mechanical energy from the engine is used to power the plasmatron. Based on prior art studies conducted utilizing hydrogen to power internal combustion engines, pollutants can be reduced dramatically. The suitably designed plasmatron according to the invention provides an efficient and compact unit to produce hydrogen-rich gas from gasoline, diesel, and other fuels. The plasmatron utilizes electrical heating of ionized gases, providing a highly controllable means to process hydrocarbon fuel. Use of the plasmatron to produce hydrogen-rich gas eliminates the need for on-board hydrogen storage on motor vehicles and will significantly improve the vehicles' working characteristics without any radical modification of engine design and fuel equipment. In addition to producing hydrogen-rich gas for the engine, the plasmatron provides a means of injecting high temperature combustible gas into the engine which can further increase completeness of combustion thereby further reducing pollutants.

20

### BRIEF DESCRIPTION OF THE DRAWING

Fig. 1 is a cross-sectional view of a water plasmatron for use in the present invention.

Fig. 2 is a block diagram illustrating the use of hydrogen-rich gas from a plasmatron as an additive to gasoline for an internal combustion engine.

Fig. 3 is a block diagram illustrating use of hydrogen-rich gas from the plasmatron as the sole fuel for an internal combustion engine.

Fig. 4 is a block diagram illustrating intermittent plasmatron use.

Fig. 5 is a block diagram illustrating operation of a plasmatron internal combustion engine system with different kinds of fuels.

30

Fig. 6 is a block diagram illustrating use of hydrogen-rich gas from a plasmatron in a hybrid, zero emission vehicle.

Fig. 7 is a block diagram of energy and mass flow in the system.

Fig. 8. is a cross-sectional view of a partial oxidation plasmatron which is vortex and magnetically stabilized.

Fig. 9 is a cross-sectional view of a partial oxidation plasmatron having a concentric electrode design.

Fig. 10 is a block diagram illustrating a plasmatron as an additional preheat source for a conventional partial oxidation reformer.

10

### DESCRIPTION OF THE PREFERRED EMBODIMENT

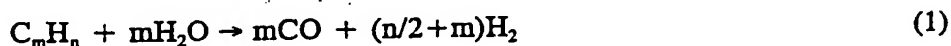
A key aspect of the present invention is a compact plasmatron or reformer which uses a plasma -- an electrically heated gas -- to convert hydrocarbon fuels into hydrogen-rich gases. One suitable configuration of a compact plasmatron is shown in Fig. 1. A plasmatron 10 includes a cylindrical cathode 12 and an anode 14. Upon energization, a plasma arc 16 is created across the anode 14 and cathode 12. Water 18 resides in the region between the cathode 12 and anode 14 and is fed in through a channel 20. A magnetic coil 22 serves to rotate the arc 16 so that it does not erode the electrodes 12 and 14. An illustrative water plasmatron 10 is described in more detail in USSR Patent No. 700935 issued August 1979. See also, Kaskey G. et al., Hydrogen Production by the Huls Plasma-Reforming Process, Hydrogen Energy Progress VI, Vol. 1, July (1986) which describes large-scale plasmatron use. It is expected that compact plasmatrons can produce hydrogen-rich gases from gasoline and other hydrocarbon fuels with greater than 90% efficiency (conversion of electricity into thermal processing energy). The hydrogen content of gas is maximized in a water plasmatron in which steam is the working gas. The plasmatron output can be 75-80% H<sub>2</sub> and 20-25% CO. Other configurations of plasmatrons could also be used such

as described by D.R. MacRae in Plasma Chemistry and Plasma Processing, Vol. 9, No. 1, 1989.

In the plasmatron 10, a mixture of hydrocarbon fuel, hydrogen and water is heated in the plasma 16 to 1,000-3,000°C at atmospheric pressure.

5 The high temperature achieved in the plasma increases the desired reaction rates resulting in highly efficient conversion of hydrocarbon fuels into hydrogen-rich gas without the use of catalysts. As a result of the large reaction rates in the plasmatron 10, the size of the plasmatron reformer is substantially decreased making it an ideal component in a vehicular system.

10 Gaseous or liquid hydrocarbons are converted by steam in the plasma by the reaction:



15 (where m and n represent the relative amounts of carbon and hydrogen) producing a hydrogen-rich gas. Temperatures in the 1,000-1,700°C range are required by the reaction kinetics. See, for example, Suris, A.L., *Handbook of the Thermodynamic High Temperature Process Data* (1987). Since it has been demonstrated that the addition of hydrogen to gasoline results in a very  
20 complete oxidation of the gasoline, it is also to be expected that the carbon monoxide, CO, would be completely burned. Since the high temperature and substantial hydrogen concentration of plasma gas will improve the efficiency of combustion in the engine it should be possible to utilize lower cost, low octane fuel instead of more expensive, high quality gasoline. Moreover, the  
25 plasmatron can process other fuels for internal combustion engines in addition to gasoline. These fuels include ethanol, methanol, natural gas, JP4 and possibly oil and biomass. The capability of the plasmatron to process different fuels provides the option of using fuel from one tank for the generation of hydrogen-rich gas and combining the hydrogen-rich gas with gasoline or some  
30 other fuel from another tank.

An illustrative plasmatron system for vehicular application weighs less than approximately 30 kilograms and has a length of approximately 30 centimeters. Plasmatron power levels are in the range of a few kilowatts. The plasmatron 10 can be used in continuous or intermittent operation to optimize performance. A small amount of hydrogen is stored in the intermittent operation mode.

With reference now to Fig. 2, the hydrogen-rich gas from the plasmatron 10 is introduced into an internal combustion engine 30 of conventional design. It is well understood by those skilled in the art how to modify an internal combustion engine to operate on a mixture of hydrogen gas and gasoline or entirely on hydrogen gas. As shown in Fig. 2, in addition to the hydrogen-rich gas from the plasmatron, hydrocarbon fuel 32 is introduced into the engine 30 as well. Some of the mechanical energy produced by the engine 30 is used to run a generator/battery system 34, the electrical output of which is connected to the plasmatron 10 for its operation. As discussed in co-pending application serial no.08/089,038 filed July 9, 1993, the plasmatron 10 requires on the order of 100 volts for its operation.

With reference now to Fig. 3, the plasmatron 10 generates hydrogen-rich gas which is the sole fuel input to the engine 30. Note that a combustion product of hydrogen,  $H_2O$ , is supplied to the plasmatron 10 for its operation. As shown in Fig. 4, the plasmatron 10 may be operated continuously or intermittently. The hydrogen rich gas can be stored in a gas storage container 36 allowing the plasmatron to operate where it is most efficient. Gas from the gas storage container 36 is introduced into the engine 30 for use under variable load conditions.

The plasmatron 10 (see Fig. 5) can operate on a variety of fuels. Hydrocarbon fuel in a tank 40 may be, for example, low octane, less expensive gasoline. A higher octane gasoline is stored in a second hydrocarbon fuel tank 38. In this mode of operation, the higher quality fuel is reformed into hydrogen-rich gas in the plasmatron 10 and then introduced into



the engine 30. Simultaneously, lower quality, less expensive, fuel is delivered to the engine 30 from the tank 40. A hydrogen-rich gas from the plasmatron 10 can be used for the gasoline engine 30 in a hybrid vehicle (see Fig. 6). A hybrid vehicle might use a gasoline engine 30 which is most efficient at steady speeds for sustained highway travel and batteries 42 for city driving.

The prior art has recognized that by optimizing hydrogen-conventional fuel mixtures in an internal combustion engine, it is possible to significantly decrease  $\text{NO}_x$  and CO by factors of 2-10; CO and  $\text{NO}_x$  reductions by factors of 5 and 8, respectively, were obtained with hydrogen addition as low as 7% by mass. See the Chuveliov reference cited earlier. Studies of the effect of hydrogen addition on gasoline engine truck operation in town driving were made with engine operation that used a variable amount of hydrogen mass fraction as set forth in the Belogub et al. article cited above. The mass fraction varied from approximately 4% to 20% depending upon engine load. Results from these studies are shown in Table 1:

Table 1  
Effects of Hydrogen Addition Upon Gasoline Engine Performance  
Toxic Components

Fuel	Payload kg	Petrol Consumption l per 100 km	$\text{H}_2$ Consumption kg per 100 km	Toxic Components		
				CO	$\text{g kW}^{-1}\text{h}^{-1}$ CH	$\text{NO}_x$
Petrol	300	34.6		86.3	2.98	14.8
	4000	38.3				
Petrol/ $\text{H}_2$	300	20.3	2.155	9.35	1.57	2.08
	4000	23.2	2.305			

The average mass fraction of hydrogen  $m_h/(m_h+m_g)$  where  $m_h$  is the hydrogen mass and  $m_g$  is the mass of gasoline was 12%. The fuel efficiency (related to the energy content of the gasoline and hydrogen) was 17.5% higher

for engine operation with the hydrogen additive relative to operation with gasoline alone.

Due to the many variables involved in internal combustion engine operation, the quantitative advantages obtained through the addition of hydrogen can vary substantially. Very large reductions in  $\text{NO}_x$  are possible through extremely lean engine operation made possible by the use of hydrogen as set forth in the Breshears article cited above. For diesel engines, hydrogen addition slightly increases the  $\text{NO}_x$  and HC emissions while decreasing the CO and smoke and increasing the efficiency.

The overall system efficiency of the invention can be projected by an energy balance. Fig. 7 shows an illustrative energy and mass flow diagram for the system. In Fig. 7, the variable  $x$  is the mass fraction of gasoline into the plasmatron;  $\rho_r$ , the ratio of the heating value of hydrogen-rich gas and gasoline, is equal to 1.3. A given mass of gasoline (or some other fossil fuel) is combined with hydrogen-rich gas to create an energy value equivalent of 12% mass fraction of hydrogen. This mass is the average value set forth above in Table 1. The hydrogen-rich gas is produced from gasoline by the plasmatron 10. For example, for the case of around 12% addition of hydrogen gas by mass mentioned previously, the amount of energy that must be added to the gasoline is 16.8 MJ/kg gasoline. This amount of energy would be produced by a 62% mass addition of hydrogen-rich gas. To produce this amount of hydrogen-rich gas it is necessary to process an additional 28% of gasoline according to equation 1.

The electrical energy requirement for the plasmatron 10 to process a given amount of hydrocarbon fuel can be given by the ratio parameter:

$$R_g = \frac{E_g}{E_p} \quad (2)$$

where  $E_g$  is the chemical energy content of the gasoline that is processed and  $E_p$  is the electrical energy requirement of the plasmatron.

The value of  $R_g$  is determined from the specific power requirement for equilibrium steam conversion of liquid hydrocarbons. See, Suris, A.L.,

5 *Handbook of the Thermodynamic High Temperature Process Data* (1987).

There is a wide range of  $R_g$  values that could be applicable.  $R_g$  is between 3 and 4 for different grades of gasoline.  $R_g$  is 5.7 for methanol. Using the value of  $R_g = 3.5$  in Eq. (2), the electrical energy requirement of the plasmatron is then  $1/3.5 E_g$ .

10 As mentioned previously, for a given amount of gasoline that is used in the internal combustion engine 30, an amount of gasoline which is approximately 28 percent as much (0.28Mg) must be processed by the plasmatron 10 to produce the required hydrogen. Therefore, the required plasmatron 10 energy to add 12 percent hydrogen by mass is:

$$E_p = \frac{0.28 E_g}{R_g} \quad (3)$$

15 or

$$E_p = \frac{0.28 E_g}{3.5} = 0.08 E_g$$

The mechanical energy requirement to operate the generator 34 that runs the plasmatron 10 depends upon  $E_p$  and  $\eta_{gen}$  where  $\eta_{gen}$  is the generator 34 efficiency. For  $\eta_{gen} = 0.9$ , the mechanical energy needed to run the  
20 plasmatron 10 is:

The net mechanical energy available for powering a vehicle is:

$$E_{mech, plasma} = \frac{E_p}{0.9} = \frac{0.08 E_g}{0.9} = 0.09 E_g$$

$$E_{mech, net} = \eta_e (1.36 E_g) - \frac{E_{plas}}{\eta_{gen}} \quad (4)$$

where  $\eta_e$  is the thermal efficiency of the engine 30. The heating value of the fuel that goes into the engine, 1.28 units of gasoline, is increased by the energy added to the 0.28 units with the energy provided by reformation. The total heating value is:  $1 + 0.28 \times \rho_{reformer} = 1 + 0.28 \times 1.3 = 1.36$ , where  $\rho_{reformer}$  is the ratio between the heating value of hydrogen-rich gas and gasoline.

Combining (3) and (4),

$$E_{mech, net} = \eta_e (1.36 E_g) \left(1 - \frac{0.28/1.36}{R_g \eta_e \eta_{gen}}\right) \quad (5)$$

If  $\eta_e = 0.25$  and  $\eta_{gen} = 0.9$  and  $R_g = 3.5$  (5) becomes:

$$E_{mech, net} = \eta_e (1.36 E_g) (1 - 0.26)$$

$$10 \quad \text{or } E_{mech, net} = 0.74 \eta_e (1.36 E_g) = 0.25 E_g.$$

The overall fuel economy of the hydrogen additive engine 30 embodiment is the net mechanical energy divided by the amount of fuel:

$$(fuel\ efficiency)_{H_2, gas} = E_{mech, net} / 1.28 m_g = 0.20 \frac{E_g}{m_g} \quad (6)$$

15 In contrast, for an engine operating with pure gasoline, it can be assumed that the thermal efficiency would be 17.5 percent lower (Table 1) and

that the fuel efficiency of gasoline-only engine operation would be  $0.21 E_g/m_g$ . Thus under these assumptions, the addition of hydrogen-rich gas could result in almost the same overall fuel efficiency.

In addition, operation on 100 percent hydrogen-rich gas, either  
5 continuously or at selected periods of time, could be attractive for certain special situations.

In general, a variety of tradeoffs between hydrogen mass fraction, compression ratio, timing, and overall system efficiency may provide more optimum operating parameters.

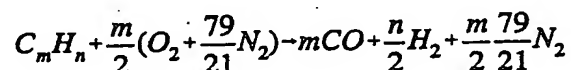
10 Using advanced control technology (already implemented in modern fuel injected vehicles), it is possible to develop an engine system where operation can be readily switched during driving between 100% gasoline operation, hydrogen additive operation and 100% hydrogen-rich gas operation.

If overall fuel efficiency were, in fact, to be significantly lowered, one  
15 option is for vehicles to use the plasmatron-hydrogen pollution reduction option when operating in cities and bypass it when operating in the countryside where  $NO_x$  and CO concentrations are lower. A further option is to use the plasmatron-generated hydrogen mainly at rpm ratings, engine temperature and outside air pressure and humidity where exhaust emissions are the largest,  
20 where control would have the greatest impact.

The plasmatron-internal combustion engine system will also be useful for hybrid vehicles that use a combination of battery-generated electrical power and an internal combustion engine. In hybrid vehicles, the internal combustion engine can be operated at loads which maximize efficiency ( $\eta_e$ ).  
25 However, in ordinary operation with gasoline, there can still be significant amounts of undesirable engine emissions. Use of a plasmatron to produce hydrogen-rich gas would reduce these emissions. Moreover, because the engine would be operating at high efficiency, the effect of the plasmatron electricity requirement on overall power balance would be minimized. In  
30 addition, the presence of a significant battery capability in the hybrid vehicle

would allow more flexibility in operation of the plasmatron. Operation of the plasmatron for producing 100 percent hydrogen-rich gas would be facilitated. Thus use of a plasmatron-hybrid vehicle system might provide capability approaching zero emission of hydrocarbons, NO<sub>x</sub> and CO. In addition, there  
 5 would be greater flexibility in operating on different types of fuel.

In yet another aspect of the invention, the plasmatron is used in a partial oxidation reforming mode rather than as a water plasmatron. In this mode, the plasmatron is employed to provide the optimal temperature for a rich mixture of hydrocarbon fuel and air. The reaction in a partial oxidation  
 10 plasmatron is:



Since this plasmatron reaction is exothermic it is possible to use it in modes where less energy is required as compared to steam reforming. A  
 15 greater range of operating conditions is possible and there is no decrease in overall system efficiency. The plasmatron provides well controlled heating which, in conjunction with the heat provided by the exothermic reaction and any other heat provided by exhaust gases or additional combustion, produces the optimal temperature for reforming. Use is made of high temperature  
 20 plasmatron off-gas for preheating the initial feed stock reagents.

NO<sub>x</sub> production in the partial oxidation plasmatron is inhibited by the rich fuel mixture in a strongly reducing environment. Use of plasmatron heating allows rapid startup and gas flow rate variation of a partial oxidation reforming system. The partial oxidation plasmatron can be used to provide  
 25 the optimal temperature for reforming both with and without a catalyst to speed up reaction rates.

With reference now to Fig. 8, a partial oxidation plasmatron 50 includes a water cooled cathode 52 which is made preferably from Zr or Hf which have high electron emissivities in oxidizing atmospheres. An anode 54 is electrically insulated from the cathode 52 structure by insulators 56. A magnetic coil 58 is provided for rotating and stabilizing an arc 60. Air is introduced tangentially at 62 in order to rotate the plasma arc 60. A hydrocarbon is introduced at 64 and mixes with the air introduced through the port 62. Reformed gases are passed into a heat exchanger 66 which serves to preheat air introduced into the plasmatron 50 through the port 62.

With reference now to Fig. 9, a partial oxidation plasmatron 70 having a concentric electrode design is illustrated. In this embodiment, a copper, water cooled electrode 72 has a coaxial configuration and can utilize different types of working gases as well as an air-hydrocarbon mixture. An arc 74 spans the region between the cathode 72 and a water cooled anode 76. In this embodiment, a hydrocarbon is introduced through a port 78 and air is introduced through a port 80. The hot off-gasses pass through a heat exchanger 66 and air is preheated before entering the plasmatron 70 through the port 80.

It is also contemplated to use a plasmatron to provide controllable preheat to a conventional partial oxidation reformer (which uses combustion heating with or without a catalyst). Such a system configuration is illustrated in Fig. 10. The plasmatron can also be used in parallel with a conventional reformer or an onboard storage source of hydrogen. The plasmatron would be used at times when these sources are not adequate to vehicular needs.

It is thus seen that a plasmatron hydrogen-rich gas generator internal combination engine system can provide substantial reductions in  $\text{NO}_x$  and CO emissions and would facilitate the use of fuels other than gasoline. Key features of the system are the possibility of modest or no loss in overall fuel efficiency due to the high efficiency of the plasmatron, the increase in engine

efficiency with the use of hydrogen-rich gas, and the option for use of hydrogen as an additive rather than as the entire fuel.

The major contributor to air pollution in the U.S. is the fossil-fuel powered motor vehicle. In 1987, 66 percent of the carbon monoxide emission, 5 43 percent of NO<sub>x</sub> emissions, and 20 percent of particle emissions came from motor vehicles alone. The water or partial oxidation plasmatron engine system of the invention for improving fuel combustion in internal combustion engines will have a significant effect on improving air quality.



15

CLAIMS:

1. Rotary power system comprising:
  - a source of hydrocarbon fuel;
  - a plasmatron for receiving the hydrocarbon fuel and reforming it into a hydrogen-rich gas;
  - 5 an internal combustion engine adapted to receive the hydrogen-rich gas from the plasmatron; and
  - a generator powered by the engine and connected to deliver electrical energy to power the plasmatron.
- 10 2. The system of claim 1 wherein the engine is connected to receive the hydrocarbon fuel in addition to the hydrogen-rich gas.
3. The system of claim 1 wherein the plasmatron is a water plasmatron.
- 15 4. The system of claim 1 further including a gas storage tank for receiving hydrogen-rich gas from the plasmatron and delivering hydrogen-rich gas to the internal combustion engine.
- 20 5. The system of claim 1 further including switching apparatus for selecting the relative proportion of hydrogen-rich gas and hydrocarbon fuel entering the engine.
- 25 6. Rotary power system comprising:
  - a first and a second source of hydrocarbon fuel;
  - a plasmatron for receiving hydrocarbon fuel from the first source of hydrocarbon fuel and reforming it into a hydrogen-rich gas;
  - an internal combustion engine adapted to receive the hydrogen-rich gas from the plasmatron and to receive hydrocarbon fuel from the second
  - 30 source of hydrocarbon fuel; and

a generator powered by the engine and connected to deliver electrical energy to power the plasmatron.

7. Rotary power system comprising:
- 5 a source of hydrocarbon fuel;
- a compact plasmatron for receiving the hydrocarbon fuel and reforming it into a hydrogen rich gas;
- an internal combustion engine adapted to receive the hydrogen rich gas from the plasmatron;
- 10 a generator/motor powered by the engine and connected to deliver electrical energy to the battery;
- a battery connected to receive electrical energy from the generator/motor, a portion of electrical energy being supplied to the plasmatron.
- 15
8. Rotary power system of claim 7 wherein the generator/motor works as an electric motor receiving electrical energy from the battery to generate mechanical energy.
- 20
9. The system of claim 1 wherein the plasmatron is a partial oxidation plasmatron.
10. The system of claim 9 wherein the partial oxidation plasmatron is vortex and magnetically stabilized.
- 25
11. The system of claim 9 wherein the partial oxidation plasmatron includes a concentric electrode design.

12. The system of claim 1 further including a heat exchanger for receiving off-gasses from the plasmatron and for preheating air or water introduced into the plasmatron.

5 13. The system of claim 10 wherein the plasmatron includes a cathode made from a material selected from the group of Zr and Hf.

14. The system of claim 1 further including a battery for startup and transient operation of the plasmatron.

10 15. The system of claim 1 further including an additional on board production or storage source of hydrogen rich gas.

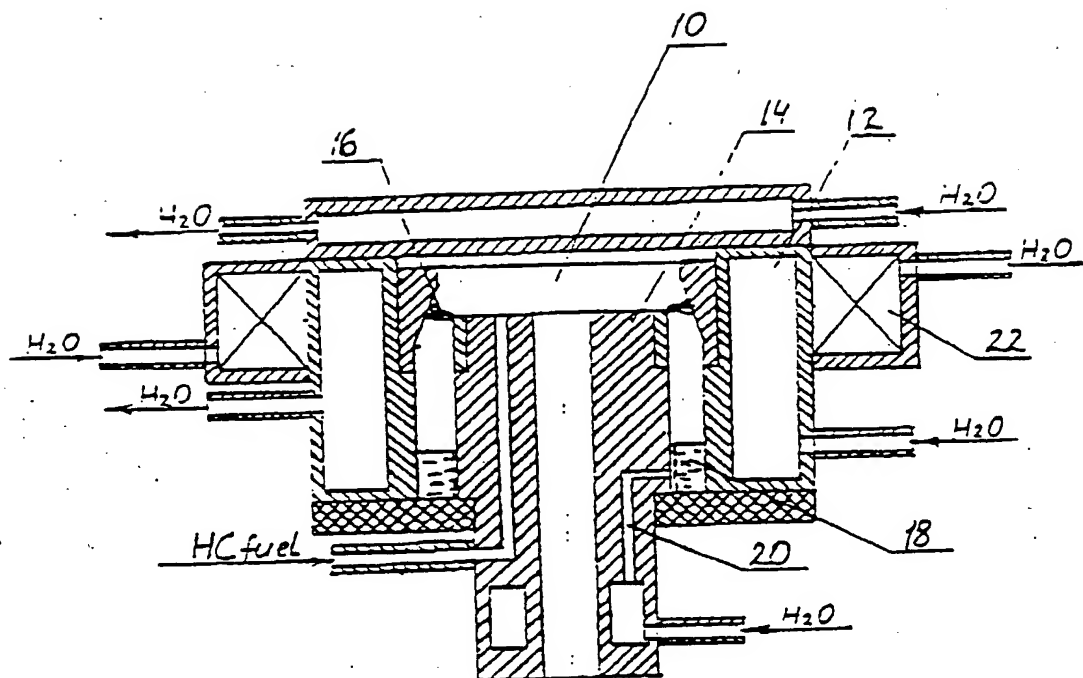


Fig 1 Water plasmatron

2/10

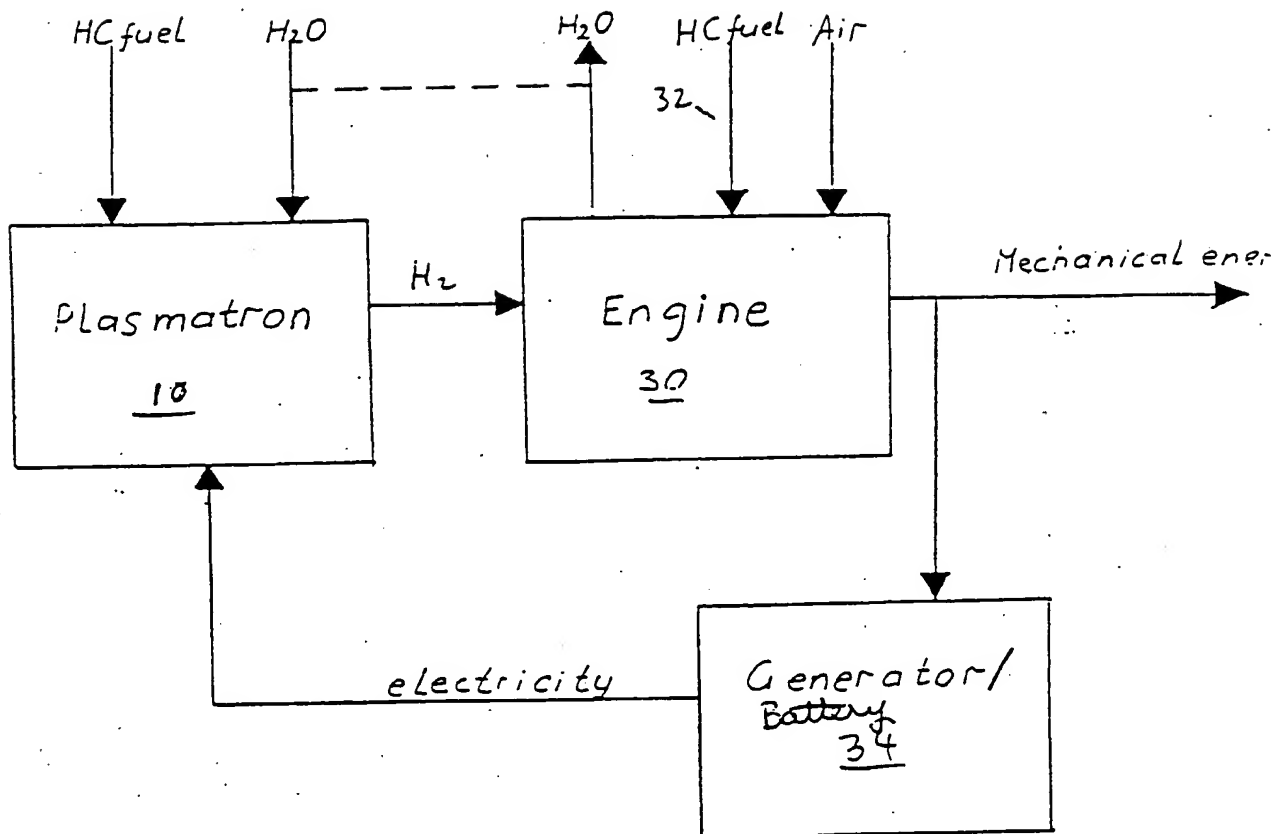


Fig 2 Use of hydrogen rich gas from  
plasmatron as additive to gasoline for engine

3/10

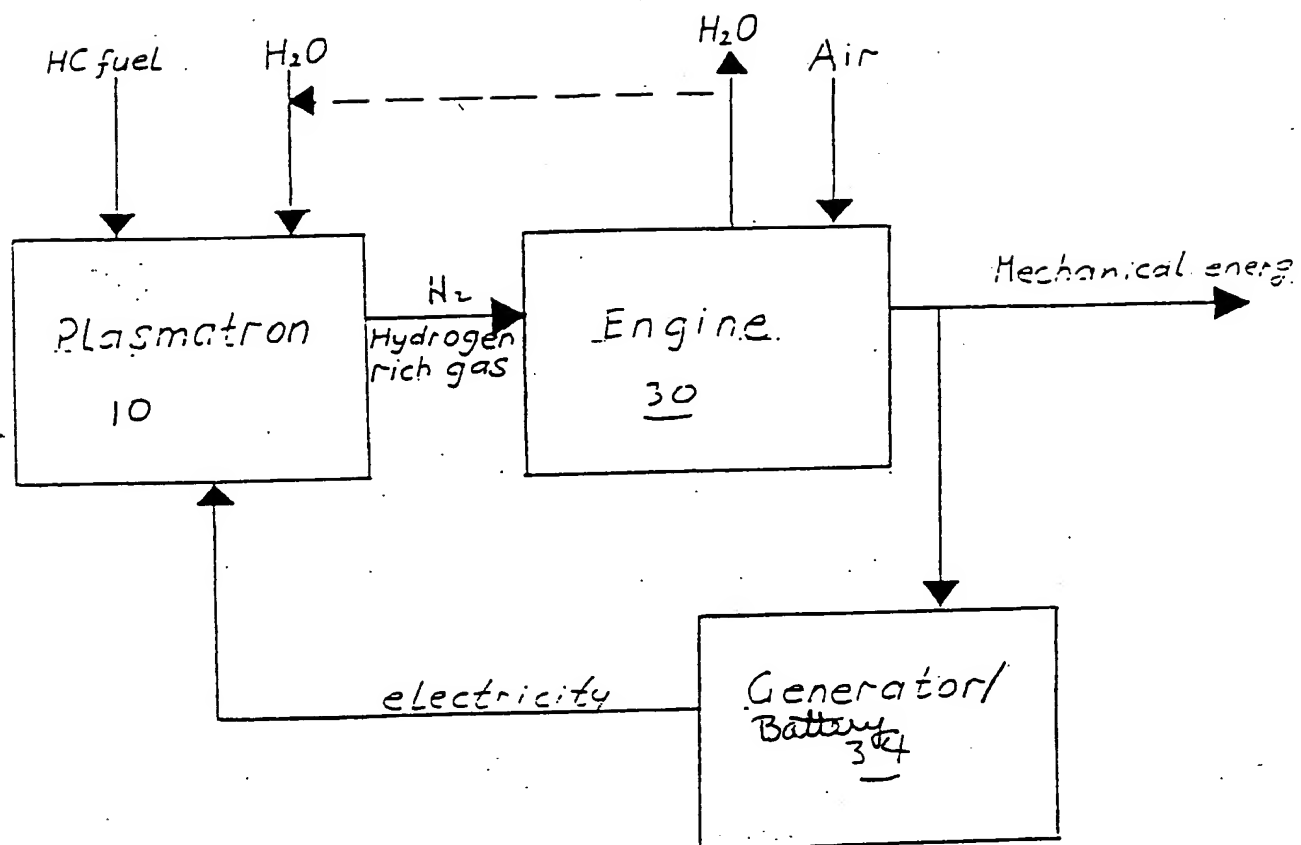


Fig 3 Use of hydrogen rich gas from  
plasmatron as a fuel for engine

4/10

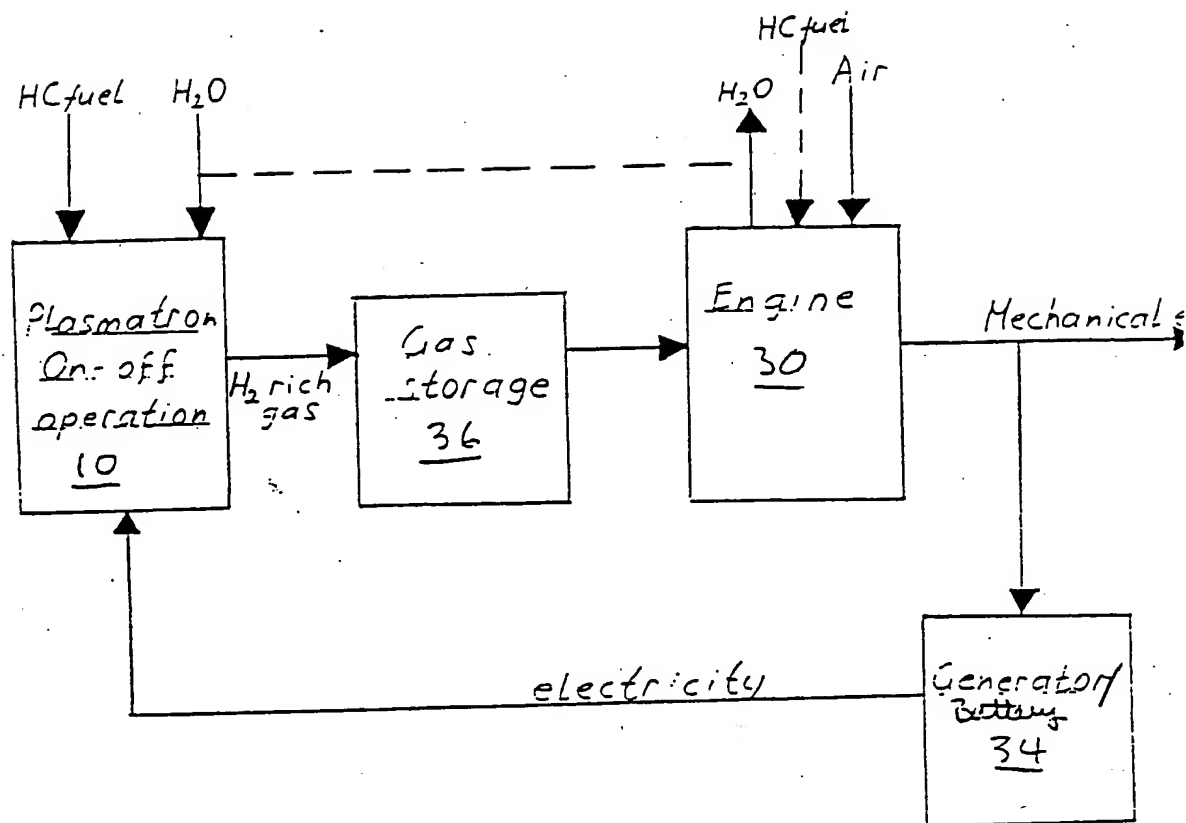


Fig. 4 Intermittent plasmatron for use for Variable Load Conditions

5/10

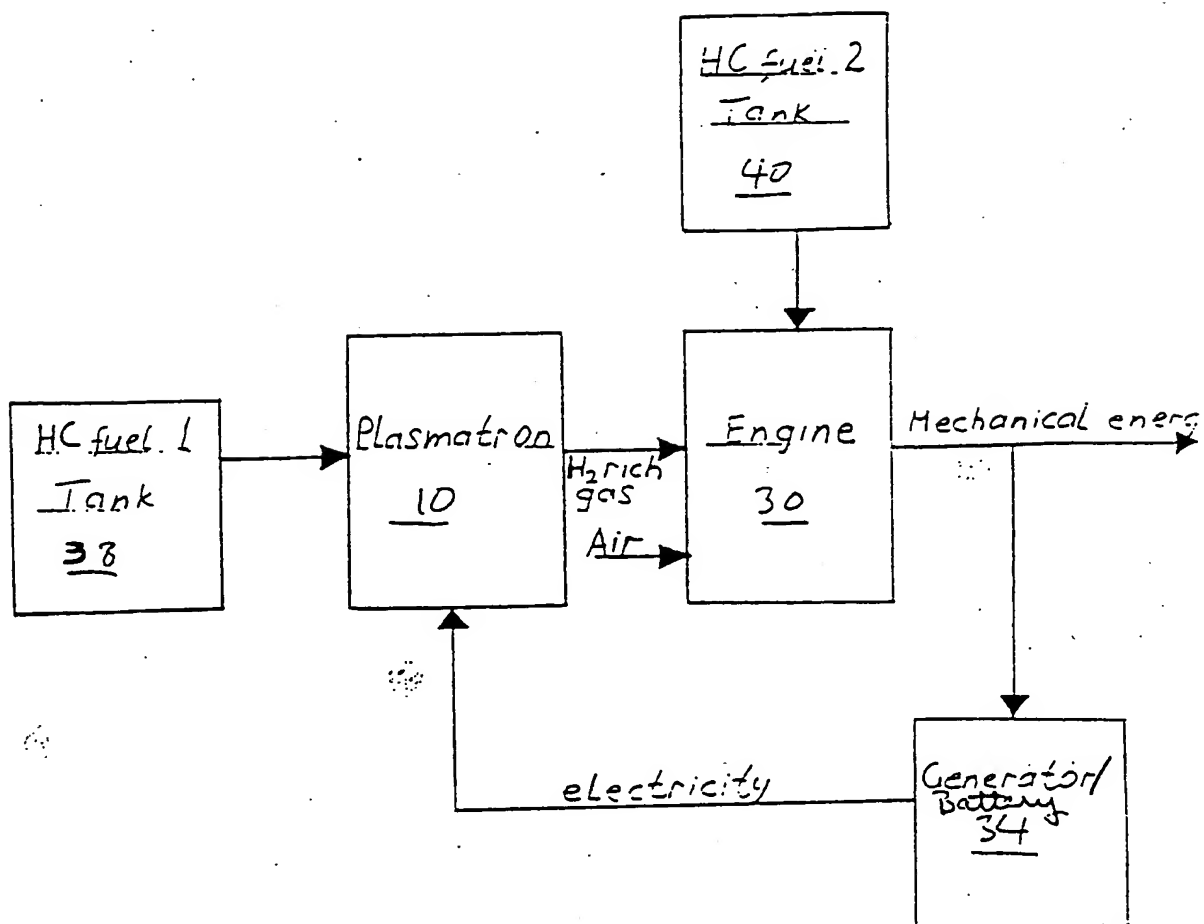


Fig. 5 Operation of plasma-motor-engine system with different kind of fuels



6/10

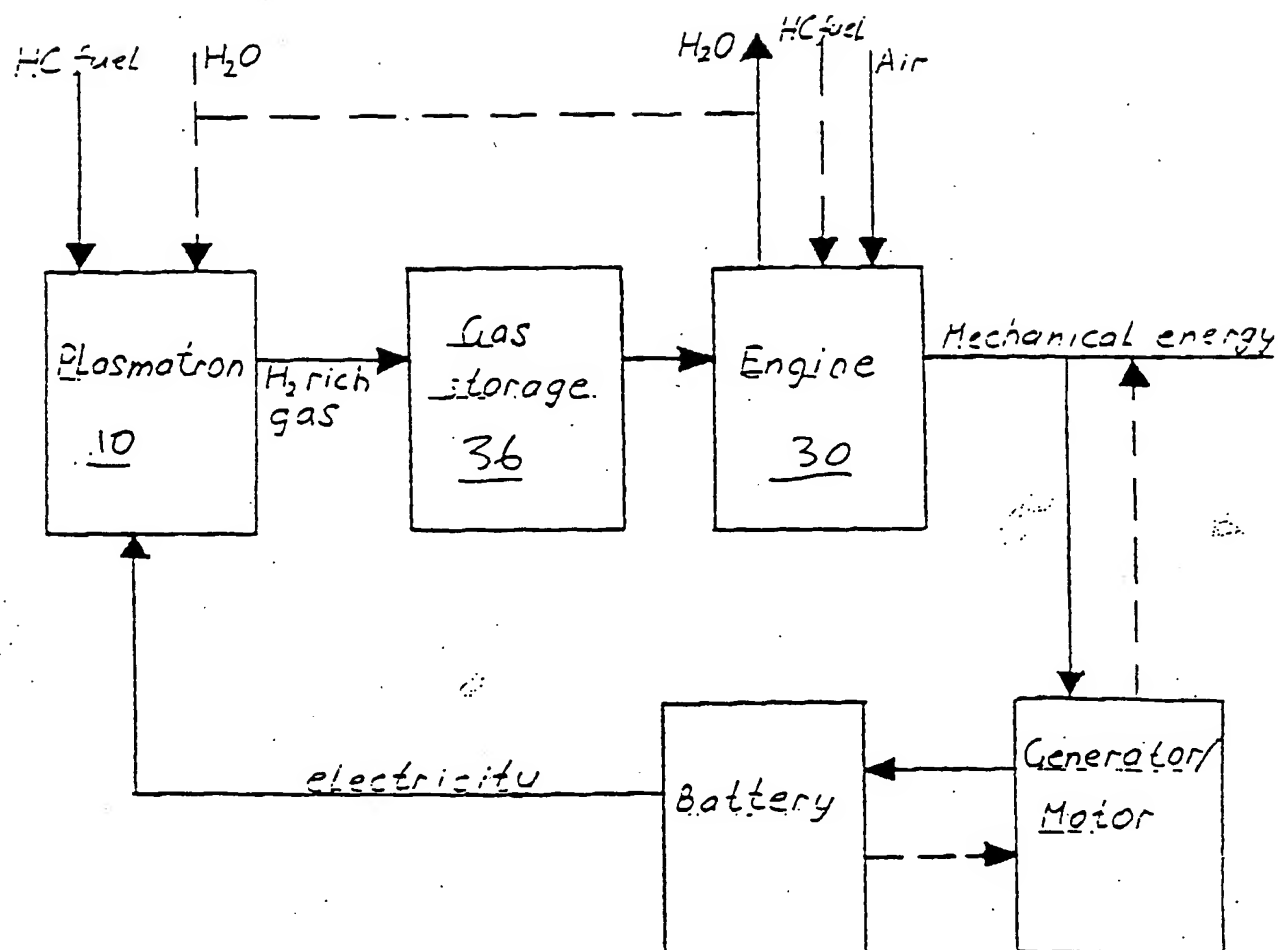


Fig. 6 Use of plasmatron in hybrid zero emission vehicle

7/10

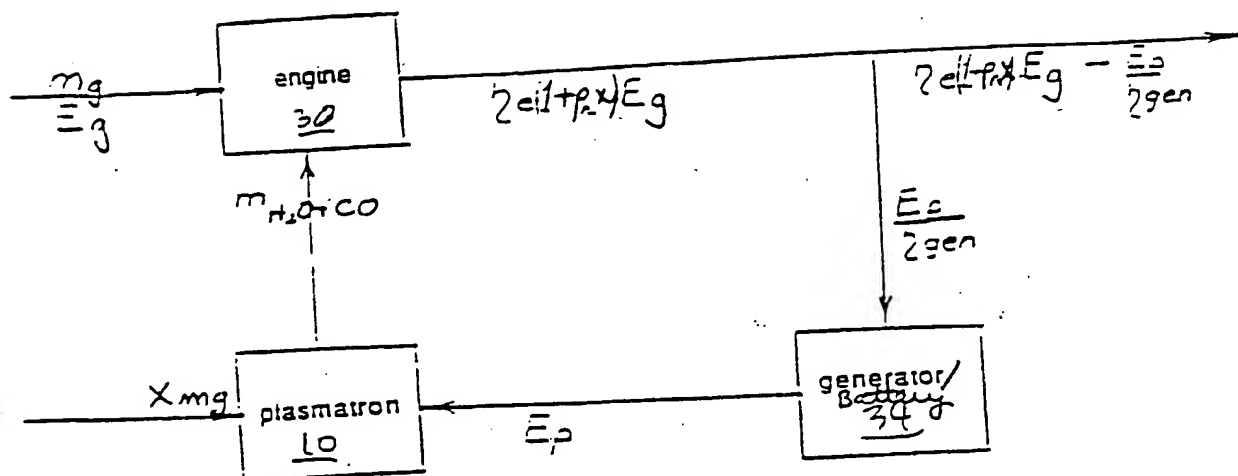


Fig. 7

Energy and mass flow diagram.

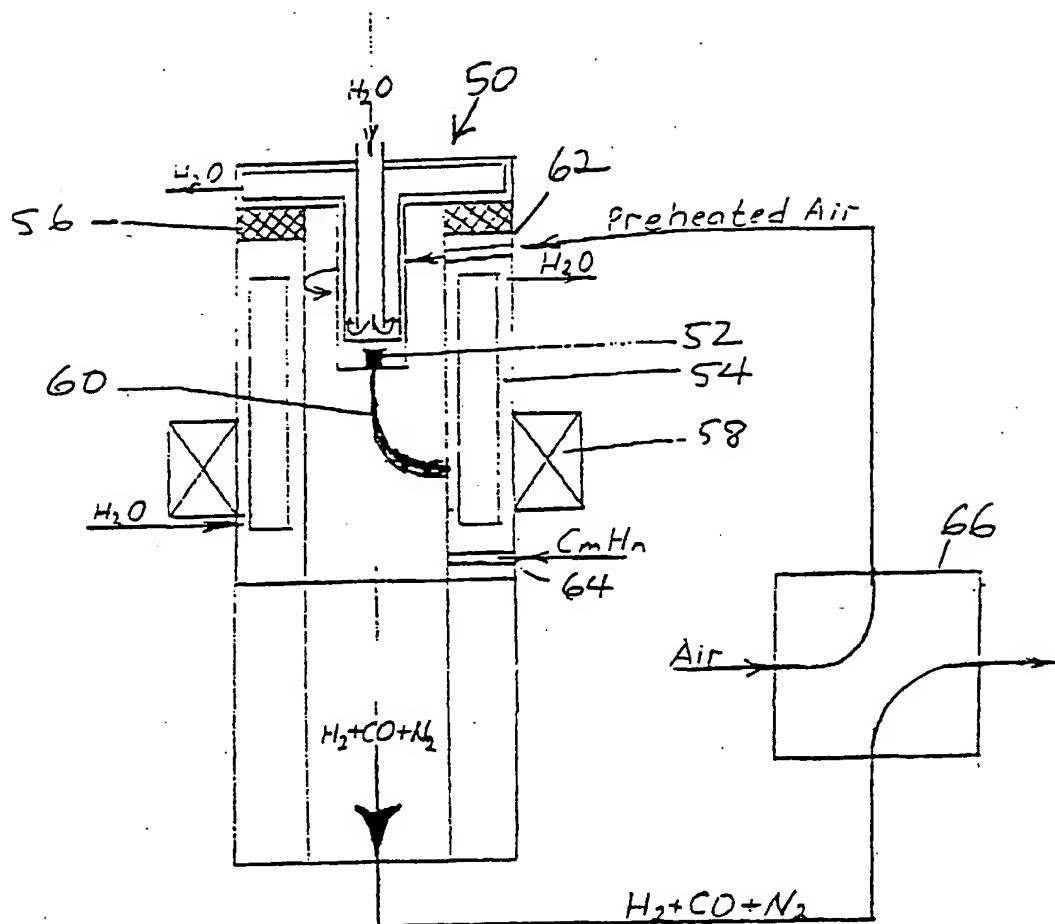


FIG. 8

9/10

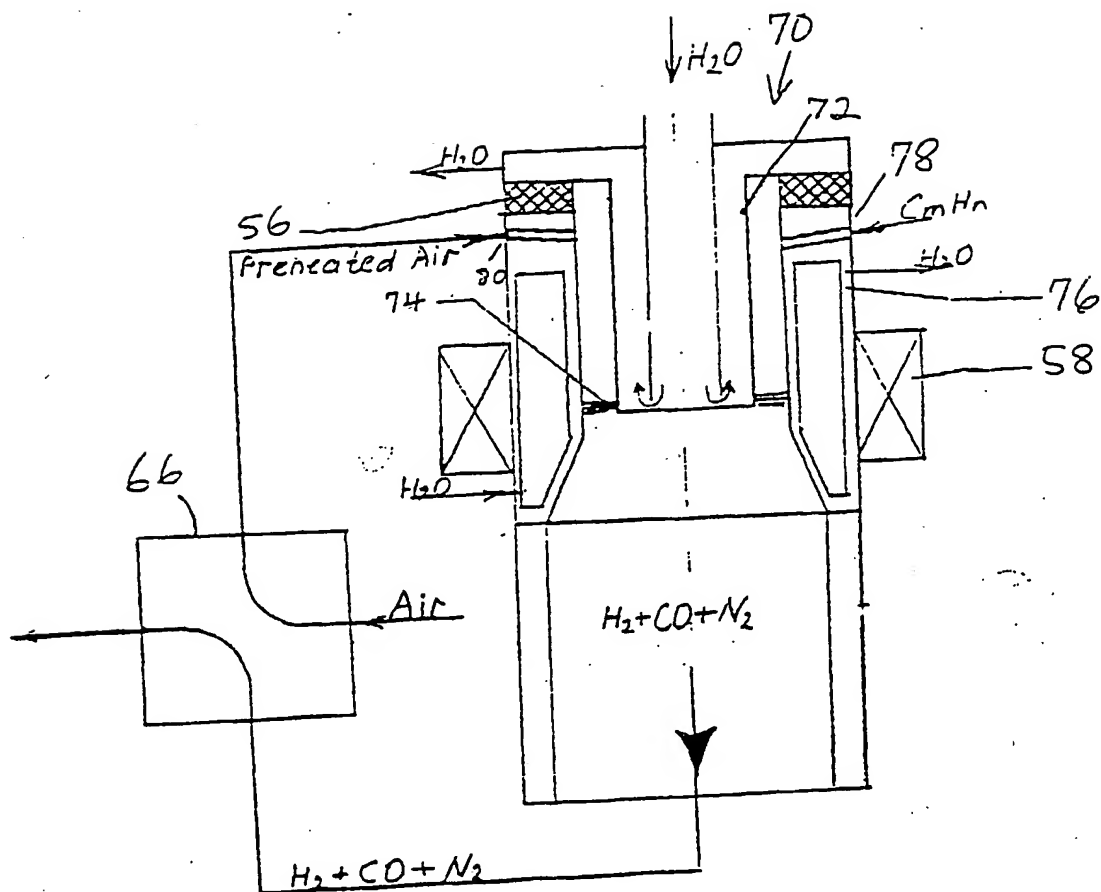


FIG. 9

10/10

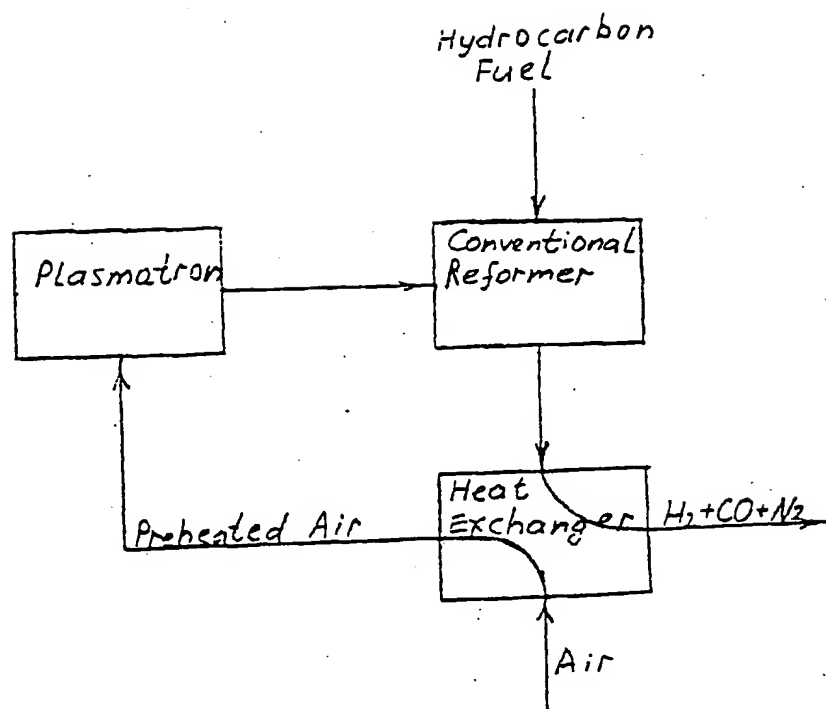


FIG. 10

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/US 94/09414

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 6 F02B43/10 F02M25/12

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 6 F02B F02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	HYDROGEN ENERGY PROGRESS VI, vol.1, 20 July 1986, VIENNA, AUSTRIA pages 185 - 190 KASKEY G. ET AL. 'HYDROGEN PRODUCTION BY THE HULS PLASMA-REFORMING PROCESS' cited in the application	1
A	---	2-4
Y	US,A,4 036 181 (MATOVICH) 19 July 1977 see the whole document	1
A	---	2-6,8
	--- -/--	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

### \* Special categories of cited documents:

- \*A\* document defining the general state of the art which is not considered to be of particular relevance
- \*E\* earlier document but published on or after the international filing date
- \*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- \*O\* document referring to an oral disclosure, use, exhibition or other means
- \*P\* document published prior to the international filing date but later than the priority date claimed

\*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

\*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

\*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

\*&\* document member of the same patent family

Date of the actual completion of the international search

5 December 1994

Date of mailing of the international search report

19.12.94

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax (+31-70) 340-3016

Authorized officer

WASSENAAR, G

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/US 94/09414

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	AUTOMOTIVE ENGINEERING, no.8, 1 August 1985, WARRENDAL, PENNSYLVANIA, USA pages 81 - 84	1
A	SCOTT & YAMAGUCHI 'HYDROGEN FUEL BREAKTHROUGH WITH ON DEMAND GAS GENERATOR'	2-9
A	EP,A,0 153 116 (SUTABIRAIZA COMPANY) 28 August 1985 see abstract; figure 1	1,7

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 94/09414

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-4036181	19-07-77	US-A- 3933434	20-01-76
		US-A- 4044117	23-08-77
		US-A- 4042334	16-08-77
		US-A- 4208373	17-06-80
		US-A- 4057396	08-11-77
		US-A- 4059416	22-11-77
EP-A-0153116	28-08-85	JP-B- 5006016	25-01-93
		JP-A- 60192882	01-10-85
		US-A- 4625681	02-12-86